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Numerical Investigation on Plastic Hinge Relocation of Reinforced Beam Column Joint Retrofitted with FRP

Balaji V
PG Student, Department of Civil Engineering,
M S Ramaiah University of Applied Sciences, Peenya 2nd Stage, Bengaluru, Karnataka, India.

Daniel Yumnam
Former PG Student, Department of Civil Engineering,
M S Ramaiah University of Applied Sciences, Peenya 2nd Stage, Bengaluru, Karnataka, India.

Dr. H M Rajashekhar Swamy
Professor and Head, Department of Civil Engineering,
M S Ramaiah University of Applied Sciences, Peenya 2nd Stage, Bengaluru, Karnataka, India.

Abstract
This paper reports on numerical investigation carried out on an exterior reinforced concrete beam column joint of a deficient model structure to study its behaviour when subjected to monotonic loads. Web bonded Carbon Fibre Reinforced Polymer is adopted for retrofitting of joints so as to relocate the plastic hinge from joint towards the beam. Numerical analysis of the retrofitted exterior joint is validated analytically. Results of the numerical nonlinear analysis on retrofitted joint shows increase in failure load and successful relocation of plastic hinge while maintaining a ductile failure with the FRP application scheme adopted.

Keywords: CFRP retrofitting, Non-linear analysis, Plastic hinge, RC joint**.**

Introduction
Collapse or failure of a structure due to earthquake commonly occurs due to failure of beam-column joints and among all the joints in a structure, exterior joints are the most vulnerable joints in a building during an earthquake. Failure to design these joints properly severely affects the overall performance of the structure.

Plastic hinges are the locations in which structural elements are allowed to undergo damage as a result of non-linear behaviour of structural materials. Hence, in earthquake resistant design, formation of plastic hinges in the beams is desirable as the imposed inelastic rotational demands can be achieved through proper detailing. However, formation of plastic hinges in the columns can lead to localized failure which will ultimately lead to global failure of the structure.

In the last two decades, there has been a sharp increase in usage of Fibre Reinforced Polymers (FRP) for strengthening RC joints as provision of FRP leads to a more ductile failure of joints whilst increasing the failure load. There are many advantages of FRPs over other techniques of retrofitting such as concrete or steel jacketing of structural members. FRPs have very high tensile strength with high strength to weight ratio, resistance to corrosion and availability in ready to apply forms (sheets or strips). The most significant advantage is that it does not increase the weight of the structure.

A. Pravin et al., 2000[1], carried out numerical investigation on the effects of retrofitting exterior RC joint with FRP. Flange bonded FRP of three different materials (E-glass, carbon and Kevlar fibre sheets) and three configurations were selected. Results indicate reduction in tension stress in rebars up to 42% and in concrete up to 26%. Flexural capacity was also enhanced up to 37%. Costas P. Antonopoulos et al., 2003[2], presented the findings of experimental tests conducted on exterior joints retrofitted with FRP sheets and strips subjected to seismic loads. 18 scaled models were used in the tests out of which 2 of them were un-strengthened. The energy dissipation and strength increased with the use of FRP but the increase is not proportionate to the layers of FRP and FRP sheets are more effective than strips. R.V.S Ramakrishna and V. Ravindra, 2015[3], presented the findings of experimental tests conducted on reinforced concrete joint subjected to static loading and proposed a rehabilitation technique for the damaged joint with GFRP. Results show an increase in load carrying capacity of the rehabilitated joint by 50% more than the original joint at the same time the deflection in the beam was reduced by 55% compared to the original joint.

Based on the literature review, an exterior RC joint from a 3-storey model reinforced concrete building designed only for gravity loads as per IS 456 2000 was chosen for the case study. ANSYS 15.0 APDL platform is adopted for performing nonlinear analysis of the joint. Reinforcement details are presented in Figure 1.

Analysis of RC Joint

Literature suggest that for numerical analysis of beam column joint, half the length of beam and half the length of column from joint can be considered (S.S. Mahini et al., 2009)[4].

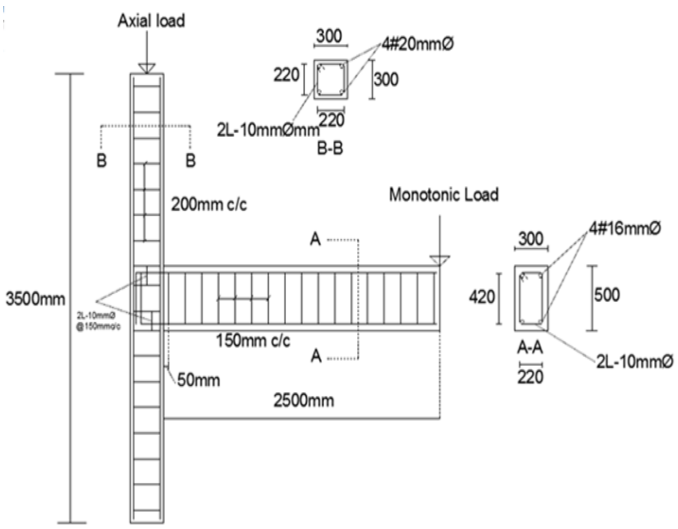

Figure 1: Joint details

Elements for Modelling the RC Joint

Element types adopted for modelling of RC joint are as follows:

Concrete: SOLID 65 elements which is dedicated for modelling of concrete with or without rebars is adopted. It has 8 nodes in which each node has 3translational DOFs in x, y & z axis. Smeared Reinforcement in up to three different directions can be modelled using this element.

Rebars: LINK 180 elements which is a three-dimensional spar element is adopted. It has 3 translational DOFs in each node. Elasticity, isotropic hardening plasticity, etc. are some of the properties supported by this element for nonlinear analysis.

Material Properties

M20 grade of concrete is used in the RC joint. Properties of concrete required for analysis are open shear elastic modulus of concrete, compressive uniaxial stress-strain relationships for concrete, shear transfer co-efficient (open and closed), ultimate uniaxial cracking and crushing stress and Poisson's ratio. Young's modulus of elasticity of concrete, E_c is taken as $5000\sqrt{f_c'}$ = 22360.6 N/mm^2 where f_c' is the characteristic strength of concrete, Poisson's ratio of 0.2 is considered. Open shear transfer co-efficient value of 0.3 and closed shear transfer co-efficient value of 0.9 was adopted (Damien Kachlakev et al., 2001, S.S. Mahini et al., 2009)[5,4]. Uniaxial cracking stress value of 2.21 N/mm^2 is adopted for predicting the failure in concrete. As pure compression failure of concrete is unlikely, crushing capability is turned off. The stress strain relationship of concrete is determined using simplified equation adopted by (Damien Kachlakev et al., 2001)[5].

$$f = \frac{E_c \varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \qquad \varepsilon_0 = \frac{2 f_{c\prime}}{E_c}$$

Where, f is stress at any strain ε; ε_0 = strain at ultimate compressive strength, $f_{c'}$

Table 1: Stress-strain relationship of concrete

Sl. No.	Stress (N/mm^2)	Strain	Sl. No.	Stress (N/mm^2)	Strain
1	6	0.00026832	4	19	0.0014087
2	13	0.0006485	5	20	0.00179
3	17	0.0010286	6	20	0.0035

Fe415 steel is considered for rebars. They are assumed to be elastic perfectly plastic material. The inputs required for defining non-linear material property of rebar are Elastic modulus of rebar = 200000 N/mm^2, Poisson's ratio = 0.3, bilinear property i.e. yield stress =415 N/mm^2 and tangent modulus is kept zero.

Boundary Conditions and Analysis Options

The model is generated in ANSYS 15.0 APDL platform as per the dimensions presented in Figure 1. The model is fixed at both ends of the column and axial load of (0.2*f_{ck}) (A. Eslami et al., 2012)[7] is applied at column top in the form of pressure. To avoid convergence problem, loading at the beam tip is applied as displacement by coupling DOF of all the nodes at beam tip and providing the displacement at single node. With this feature, convergence problem was avoided. At the end of the analysis, the force required to produce achieved displacement is generated by selecting the same node at which displacement was provided and checking structural forces in Y direction.

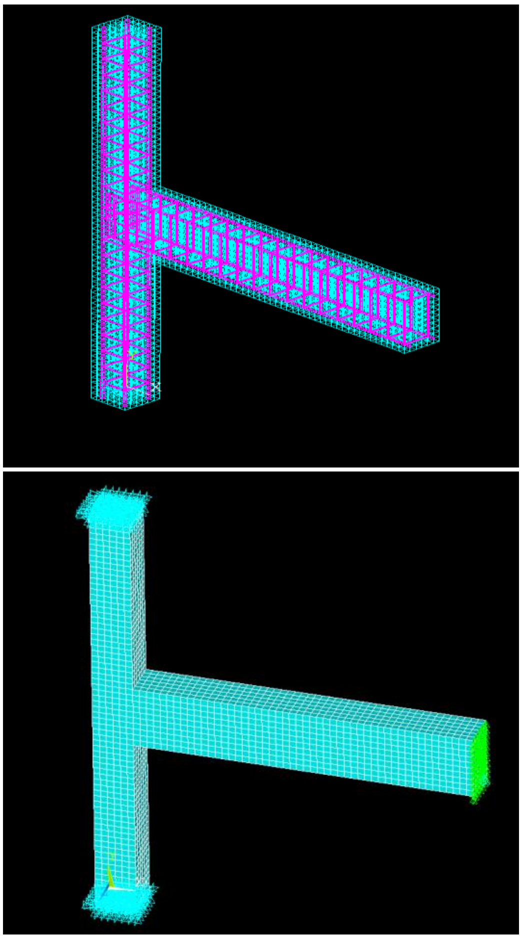

Figure 2: Models generated in ANSYS software

ANSYS adopts Newton Raphson method for solving non-linear analysis. Hence, the force and displacement convergence criteria were relaxed to 0.5% and 5% respectively in this study.

Analysis of Retrofitted RC joint

Unidirectional Carbon Fibre Reinforced Polymer (CFRP) is adopted since literature suggests that carbon fibres provide better results in terms of enhancement in failure load and control in deflection (H.R. Ronagh et al., 2013)[8].

FPR Application scheme Design

After the analysis of the original RC joint, analytical design of FRP wrapping at the joint is carried out to transfer the plastic hinge towards the beam and increase the failure load. The FRP application scheme adopted in this project is the work carried out by (Umut Akguzel, 2011)[9] and the application scheme is presented in Figure 3. 5 layers of CFRP sheets were considered for successful relocation of plastic hinge.

Table 2 Joint details and FRP scheme details

Geometric Data							
h_b	500 mm	b_c	300 mm	l_b’	2500 mm	b_w	300 mm
d	460 mm	h_c	300 mm	l_c	3500 mm	N_v	360000 N
l_b	2650 mm						
Material Properties							
F_{ck}	20 N/mm^2	E_c	22360.6 N/mm^2	f_{ct}	2.21 N/mm^2	C_1	0.64
E_f	62000 N/mm^2	t_f	1 mm	E_{fu}	1.55%	C_2	2
Beam and Column FRP Scheme							
n_{fb}	5	n_{sfb}	2	d_{fb}	500 mm		
n_{fc}	5	n_{sfc}	2	d_{fc}	300 mm		

In Table 2, d represents effective depth of beam; h_b and b_w represents depth and width of beam; h_c and b_c represents dimensions of column; l_b’ represents beam length form the face of the column; l_b represents length of beam from centroidal axis of column to extreme edge of beam; l_c represents length of column, N_v represents axial load on the column and l_{bt} and l_{bl} represents length of FRP from centroidal axis of column.

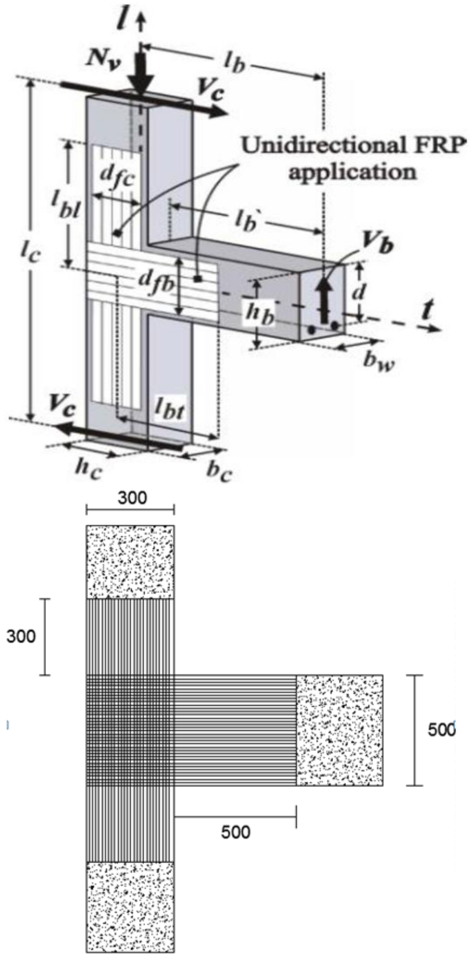

Figure 3: FRP design details (Umut Akguzel)[9]

The length of the FRP on the beam should be chosen in such a way that plastic hinge is formed in beams and does not affect the column. Therefore, a length of 500 mm is chosen from the column face.

Using the expressions proposed by the author of [9] moment in the retrofitted joint is determined.

$$M = \frac{\sqrt{Ptt^2 + Ptt\,f_v}}{\omega}(10)^3$$

M = 182.1258 kN-m

Where P_{tt} represents total principal tensile strength in the joint due to plain concrete and FRP =7.620784 N/mm^2, f_v represents the pressure in the column face = 4 N/mm^2, ω is the geometric co-efficient of joint = 51.6709.

Elements for Modelling the RC Joint

FRP: SOLID 185 element is adopted for three-Dimensional modelling of Solids. To use this element, 'n' number of layers can be modelled using this element.

Material Properties

In unidirectional FRP laminates, higher material property will be observed along the axis in which fibre is oriented and in the other two orthogonal directions, material property will remain the same. Inputs required for material modelling of FRP is the orthotropic property. Young's modulus in X, Y and Z directions are 62000, 4800 and 4800 (N/mm^2), Poisson's ration n XY, YZ and XZ directions are 0.22, 0.3 and 0.22 and finally, shear modulus in XY, YZ and XZ directions are 3270, 1860 and 3270 (N/mm^2).

Boundary Conditions and Analysis Options

FRP layers are added to the original joint as per the dimensions presented in Figure 3 and Table 2. To avoid excessive aspect ratio of FRP mesh, the total numbers of FRP layers are modelled as a single volume. Boundary condition and analysis options are the same as that adopted in above section.

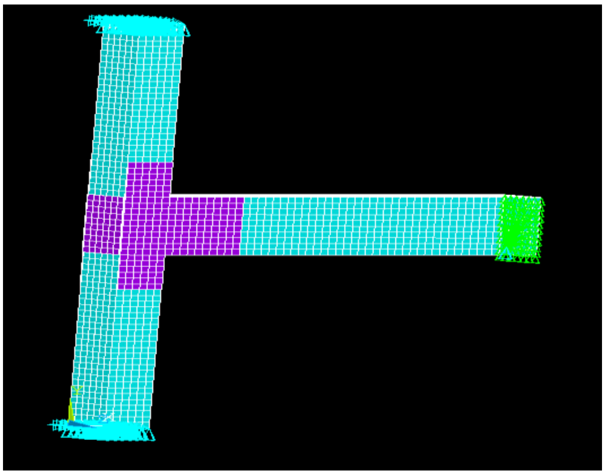

Figure 4: FRP modelling in ANSYS

Results and Discussions

The results of the numerical analysis of original joint and retrofitted joint are presented in the following section.

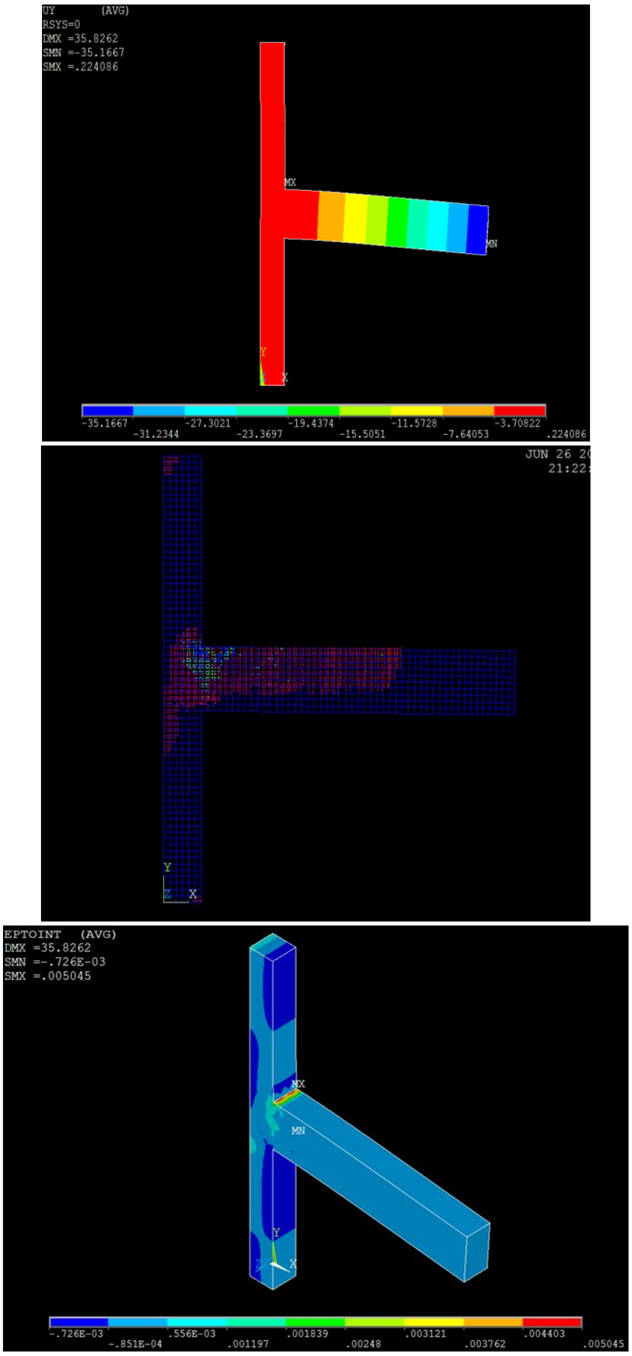

Figure 5: Results in terms of displacement, crack formation and strain concentration in the original RC joint at Failure (from the top).

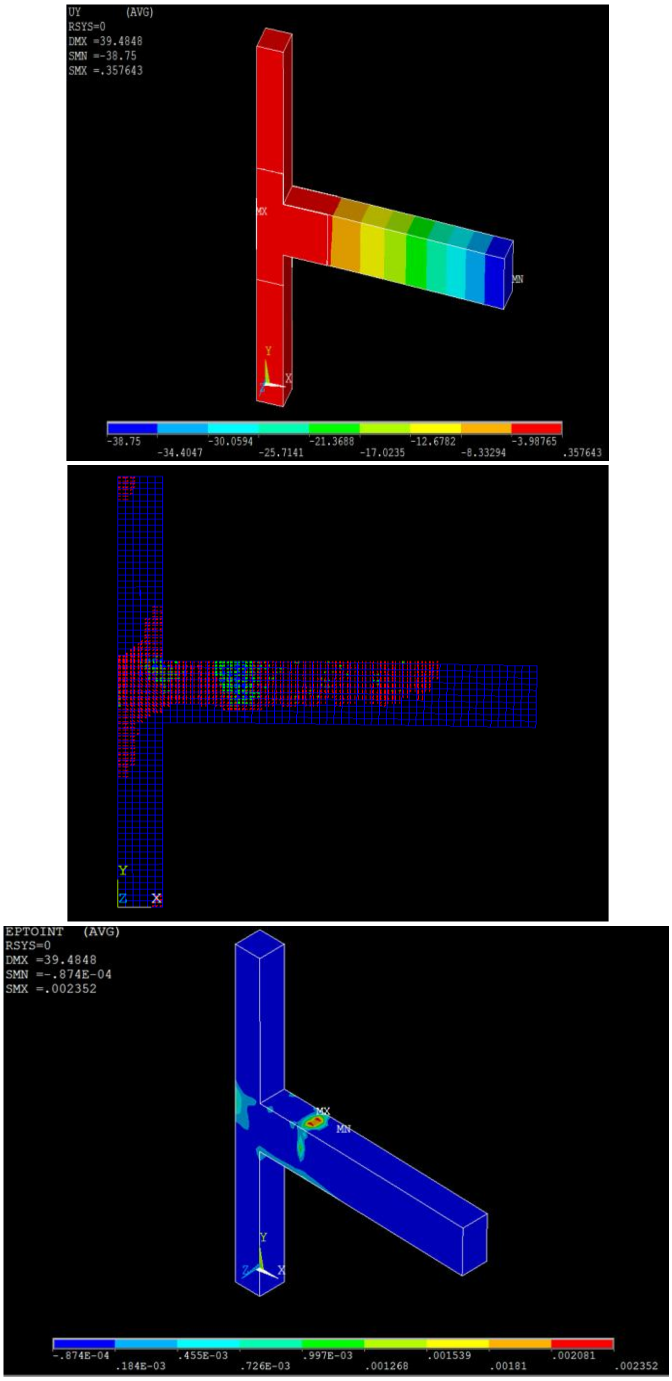

Figure 6: Results in terms of displacement, crack formation and strain concentration in the retrofitted RC joint at Failure (from the top).

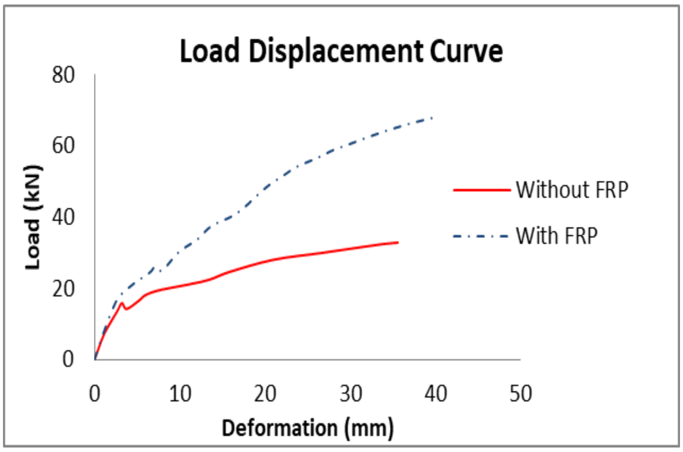

Figure 7: Comparison of load displacement curve

From Figure 5, it can be observed that maximum cracks have generated in the joint area which shows that failure has occurred in the joint. Concentration of strains at the joint indicates formation of plastic hinge at the joint. Load at failure is 32.81 kN and the corresponding displacement is 35.5833 mm.

From Figure 6, it can be seen that cracks are now concentrated more at the end of the FRP layer towards the beam which was earlier concentrated more at joint area. Concentration of strains in the beam away from joint indicates the successful plastic hinge relocation towards the beam which was the sole purpose of retrofitting the joint. Load at failure is 67.745 kN and the corresponding displacement is 39.5833 mm.

As seen in Figure 7, the retrofitted joint is able to take up more loads as compared to the original joint. The increase in the ability of the joint to carry more loads is 34.9345 kN. The percentage increase is 51.57%. Due to addition of FRP layers, the joint is able to undergo higher displacement before failure. For the same load, displacement at the beam tip is also reduced due to addition of FRP layers. Considering the failure load of the original joint which is 32.745 kN, corresponding displacement is 35.5833 mm. In the retrofitted joint, displacement at that load is about 12.083 mm. The reduction in displacement is 23.5003 mm and the percentage decrease is 66.04%.

Validation of Numerical Analysis of Retrofitted Joint with Analytical FRP Design

To determine the moment capacity of numerical model of the retrofitted joint, failure load should be multiplied by the length of beam at which it is loaded (A. Parvin, 2000; M. Bosco 2008)[1,10].

Moment capacity of Numerical analysis, M = 67.745 * 2.5 = 169.362 kN-m

Moment capacity of the retrofitted joint from Analytical method, M = 182.1258 kN-m

Here, the moment capacity from numerical analysis is in close agreement with each other with percentage difference of only 7.536% which is reasonable.

Conclusion

Modelling of beam column joint and performing non-linear analysis is a very challenging task and requires skillful knowledge before proceeding with the analysis. Retrofitting of RC joint with externally bonded fibre reinforced polymer is a viable solution and it is more advantageous than other techniques of retrofitting. FRP, if incorporated properly into a structure can lead to enhancement in its seismic performance. From the beam column joint numerical analysis, it can be seen that addition of FRP enables ductile failure of the joint. The two load displacement curves of retrofitted and original joint show that the slope after the elastic range for retrofitted joint is larger compared to that of original joint. Finally, the retrofit strategy adopted in this investigation was able to successfully relocate plastic hinge towards the beam.

Future Recommendations

Only one FRP application has been adopted in this study, further study can be done on other FRP application scheme. Experimental work on RC joint can be further carried out. Numerical analysis on Three Directional RC joint can also be carried out.

Limitations

The size of column and beam are taken equal at the joint area to reduce the difficulties and discontinuities in finite element modelling of the joint. This may not be the case in an actual structure. Due to non-availability of Standards for FRP design of beam column joint, only one retrofitting scheme has been used in this investigation which was extracted from a PhD thesis

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